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Sustainability-based economic and ecological evaluation of a rural biogas-linked agro-ecosystem

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ABSTRACT

Biogas-linked agro-ecosystems provide economic and environmental benefits by using resources in a multipurpose manner. They utilize an energy consumption pattern that has prominent advantages in relieving energy shortages and reducing environmental pollution. To better understand the effects of these multiple aspects, it is important to study how much of the energy flow is extracted and available through the biogas-linked agro-ecosystem using an economic input–output evaluation or ecological and social influence assessments. It is also equally important to understand the conversion efficiency during the life cycle of biogas production, and how humans influence the whole process of the biogas-linked agro-ecosystem. This paper attempts to establish a life cycle-based accounting model of a household biogas system using different economic and ecological metrics for multiple objective considerations, to provide a powerful and comprehensive perspective to illustrate sustainability problems. In this study we use a typical household biogas system in Gongcheng Autonomous County (Guangxi Province, China) as a case study to reveal an effective route and strategy to relieve energy shortage, reduce environmental pollution, and improve human productivity. In this way, we can construct an exemplary example of how to realize sustainable development in a rural area with positive objective conditions.

Contents

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1. Introduction

Rural areas are home to just over half of China's population, 50.05% in 2010 [1], and are an essential part of the overall economy. Ever since the Open Door policy initiated in 1978, China's rural economy has experienced incredible high-speed growth, accompanied by a trend of substantial and profound changes to its rural energy pattern [2,3]. In previous decades, villagers' per capita energy consumption was very low, mostly for cooking and heating [4], and their energy requirements were met using traditional biomass fuels [4,5]. However, in recent years, biomass fuels have been used less and less each year, with the ratio as low as 0.2% in 2006 [6]. In contrast, total primary energy consumption has increased, mainly owing to peasants' pursuit of better standards of living, with a rapid growth in the use of coal, natural gas, and electricity.

A number of facts are undisputed: (1) China has been the world's second largest energy user since 2002, of which less than 10% of the total primary energy consumption is from renewable sources [7,8]; (2) the growing trend of energy prices will somehow influence consumers' psychology in rural China; and (3) the consumption of fossil fuels directly causes serious pollution and global warming [4]. In addition, inefficient energy utilization, excessive firewood collection, and accompanying pollution have already troubled China for many decades in most rural areas [9,10]. Therefore, it is reasonable to infer that severe energy resource shortages, soaring energy economic costs, and severe environmental deterioration are the three biggest constraints restricting both China's agricultural development and peasants' living standards.

With the prevailing trend of developing renewable and sustainable energy technologies, including wind power, solar energy, and bioenergy, the application of biogas, a clean and efficient reproducible gas, has been considered as a practical approach to solving the rural energy deficit and reversing the country's health and environmental situation [11,12]. Many previous studies have demonstrated that biomass, especially for bioenergy, has the potential to become one of the major global primary energy sources in the 21th century, and modernized bioenergy systems are recommended to be important contributors to future sustainable energy systems, sustainable development in industrialized countries, and in developing countries and areas [13–17]. Biomass represents an abundant and renewable energy source because it contains more hydrogen than coal while containing less sulfur and ash. Biomass, in its gaseous or liquid form, is not only clean but also convenient. Furthermore, biofuel from biomass becomes a sink for greenhouse gases (GHG) because biomass is low in carbon and carbon is fixed during biomass growth [18]. Biomass therefore is likely to be an attractive clean development mechanism option for reducing GHG emissions [5].

There are substantial quantities of available biomass resources in rural China, namely crop straw, forest residue, livestock, poultry manure, and various household organic wastes and waste water [19]. Moreover, a wide range of existing and future technological options for cost-competitively improving biomass efficiency and reducing the negative environmental impact of biomass energy use have placed biomass at the front of other modern energy carriers, ahead of electricity, cleaning gas, and liquid fuels [20,21]. Administratively, the Central Government of China has strongly supported the development and application of biomass energy ever since the first official policy paper on renewable energy development, "Circular on Improving Rural Energy Development" was issued by the China National Economic Committee in 1986 [3,11,22]. Since then, a series of policies, laws, criteria, and projects in the fields of energy, environment, and economy have emerged, including the Central Government of the People's Republic of China [23], the National Development and Reform Committee of China [24,25], and the National People's Congress of the People's Republic of China [26]. These regulations all recognize biogas technology as an environmentally friendly measure, which, in addition to energy production, may contribute to a more efficient, economical, and safe recycling of manure to improve peasants' living and agricultural production [27].

However, it must be admitted that biomass, as a fuel source for large-scale power generation, is in its infancy not only in China, but also in many countries worldwide [28]. Therefore, suppliers and supply chains have not yet been developed on a large scale to supply the necessary bioenergy to meet extensive power requirements. Unlike mature and traditional energy supply chains, the rapid development and wide application of biogas is influenced by local environment, the availability of raw materials' for biogas production, transportation, storage, climate conditions, and supporting policies. Furthermore, the biogas utilization in China related to rural energy development and corresponding escalating economic activities, especially for biogas-linked systems, has given rise to complex interrelationships among society, economics, energy, environment, and realistic rural energy policies [9]. This has moved further forward with the purpose to develop sustainable and integrated material for energy-based agriculture and the rural economy. Hence, after a 40-year history of biogas for smallholders in rural China, the objective of developing biogas is not only to provide energy, but also to apply improved biogas technology to sustainable agricultural systems for recycling biomass [11] based on a large-scale application, such as the integrated pig-biogas-vegetable systems in northern China [29] and livestock-biogas-fruit systems in southern China [30]. For this reason, modern biogas utilization has been popularized in combination with ecological agriculture for a better performance of harmonizing economic profits, environmentally friendly development, and resource consumption optimization. We term the system the "biogas-linked agro-ecosystem" in this paper.

Frequently-used methods to comprehensively evaluate the social-economic-ecological effectiveness of complex biogas-linked agro-ecosystems are an analysis by index or factors [10,27,31–35] and model evaluation from previous research [36,37]. The former is focused on assessing the effects via economic, energetic, or physical concepts or indicators, such as emergy or exergy analysis, while the latter analyzes the mutual relationship between multi-factors within the system to gain the maximum benefit. Generally speaking, most peasants prioritize economic input and output, but from the angle of administrative departments and environmental protection, social and ecological influences are equally significant. Herein, on the basis of previous research, we provide an economic cost-benefit analysis for life cycle biogas-linked agro-ecosystem modification works. Extended exergy has also been chosen as an evaluation tool in this study. (This is an "embodied" measure for the equivalent primary exergy resource consumption as well as an extension of traditional exergy analysis by including socio-economic factors such as labor and capital costs in physical terms of the equivalent primary resource consumption.) First, it is widely accepted that the exergy-based assessment can be correctly regarded as a physical and thermodynamics-based metric to evaluate the scarcity and utility of ecological resources. Furthermore, extended exergy is a new application metric to evaluate the comprehensive social-economic-ecological effects of biogas-linked agro-ecosystems [38–40]. Extended exergy analysis (EEA) is a socio-economic construct with biophysical references, intended to reconcile the labor theory of value and the current thermodynamic theory. It is a suitable tool to measure the cost of sustainability because it is well known that most measures aimed at increasing the degree of sustainability of a society require greater resource consumption at the onset [41]. So far EEA has been applied to different societies and scales in the literature for social and economic sustainability

analysis (e.g., Norway [42], Italy [43], Siena, a province of Italy [44], the United Kingdom [45,46], the Dutch energy sector [47], Turkey [48], and China [49]. However, the study presented in this paper is the first EEA application to a regional project from a life cycle analysis perspective.

There are different types of biogas-linked agro-ecosystems in China. Here we chose Gongcheng Yao Autonomous County, a typical livestock-biogas-fruit system in south China, as the target area. The county lies in the northeast part of the Guangxi Zhuang Autonomous Region. In 1990, Gongcheng developed the “three-in-one” mode of biogas-linked agro-ecosystem, which linked orchard-agricultural activities and stock farming with a biogas tank and included multipurpose usages for biogas, biogas residue, and slurry. By the end of 2010, approximately 65,800 household biogas units had been constructed in Gongcheng, at a popularization rate of 91.6% and with 79.9% forest coverage [50]. This is the highest biogas popularization rate in the nation and has already been set as an example for the development of biogas-linked agro-ecosystems in China. This particular area was chosen as a case study because we wish to evaluate the comprehensive effects of building household biogas units on the benefits to peasants, social influences, and potential ecological and sustainable impacts. Furthermore, because the use of biogas in Gongcheng is considered a national example, it will be more convincing to formulate or regulate an acceptable pattern of multiple interests based on this area to further promote biogas application in rural China.

Herein, we present a comprehensive economic and ecological accounting framework based on a life cycle analysis of a biogas-linked agro-ecosystem. An input–output-based monetary analysis and an EEA-based assessment metric were applied to address synthetic benefits in which raw material, capital and labor input, and environmental influences were taken into account together. Hence, biogas-linked life construction and operation processes were compatibly inlayed in the accounting procedure. The remainder of this paper is arranged as follows. The general accounting method and system boundary are illustrated in Section 2. In Section 3, the accounting results and economic and ecological metrics analysis are demonstrated on the basis of several objective considerations. Following in Section 4, we discuss the accounting application for biogas-linked agro-ecosystems and finally, a range of conclusions are presented.

2. Methodology

2.1. Method

2.1.1. Extended exergy accounting

The *extended exergy content (ee)* of a specific flux (material, kg/s or units/s, or immaterial, J/s, €/s, workhours/s), is defined as

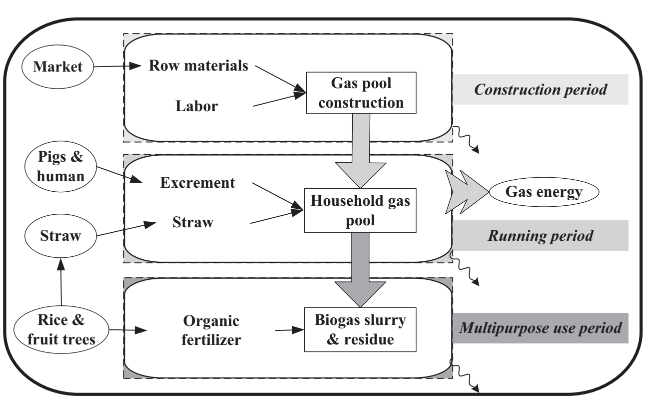

Fig. 1. Life cycle assessment framework of household biogas comprehensive utilization.

follows [51]:

$$ee = e_m + e_{phys} + ee_K + ee_L + ee_{Env} [kW/\psi], \tag{1}$$

where e_m (material exergy) is the sum of the physical and chemical exergy contents of the raw materials used in the fabrication of the item; e_{phys} (physical exergy) indicates the algebraic sum of the exergy of energy flows used in the fabrication of the item (heat, mechanical work, electrical energy, chemical energy, etc.); ee_K (capital equivalent exergy) is the exergetic equivalent of the total net monetary influx into the process; ee_L (labor equivalent exergy) is the exergetic equivalent of the sum of the labor contributions; ee_{Env} (environmental remediation equivalent exergy) is the total extended exergetic “cost” (i.e., the total amount of primary exergy resources) necessary to bring the effluent to a state of equilibrium with the environment. Generally, we combine e_m and e_{phys} together as *CEC* (cumulative exergy consumption based on resource). The specific four parts of the total extended exergy accounting are shown in Section 3.

2.1.2. Life cycle analysis

Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product’s life cycle, i.e., from raw material acquisition, production and use phases, to waste management [52]. The unique feature of LCA is the focus on products or production process from a life cycle perspective. Therefore, the comprehensive scope of LCA is useful to avoid problem shifting, for example, from one phase of the life cycle to another, from one region to another, or from one environmental problem to another [53]. Here we decompose the typical household biogas comprehensive utilization system into three periods, (1) construction period, (2) running period, and (3) multipurpose use period, based on the LCA understanding (see Fig. 1) to further and fully accomplish a substitution benefit analysis and EEA analysis. Several input and output flows are also shown in Fig. 1.

2.2. System boundary

The most common and typical household biogas system in Gongcheng was chosen for the case study. The size of its tank is 8 m^3, and the maximum service life is estimated to be 15 years. Considering the optimal usage of the system, we limited the study time to 10 years. The annual average temperature of Gongcheng is $> 10\ ^\circ C$, which is the minimum temperature for biogas fermentation; the system is theorized to function properly all year long. To make a distinction between pre- and post-construction of the domestic biogas program, we draw two figures demonstrating the variations of input output flows and metabolic process (see Figs. 2 and 3). Fig. 2 is drawn based on the primordial rural agro-ecosystem metabolic process, and Fig. 3 shows the alterations of the input–output relationship after household biogas construction, in which the blue line refers to reduction and the red line means the value increases compared with the period when there was no biogas construction. This is a representative diagram after rural biomass recycling and reuse based on one family in Gongcheng.

2.3. Data source

In Table 1, we list all primary data of a typical household biogas system in Gongcheng Yao Autonomous County, as well as the necessary economic and exergetic factors. The basic data of biogas system were sourced from the Gongcheng Economic Information Network [54], Gongcheng Agriculture Information Network [55], China Economic Information Network [56], Guilin Economic Information Network [57], and the Gongcheng County Government Network [58]. The other exergetic factors were obtained from previous studies as listed in Table 1 [59–62].

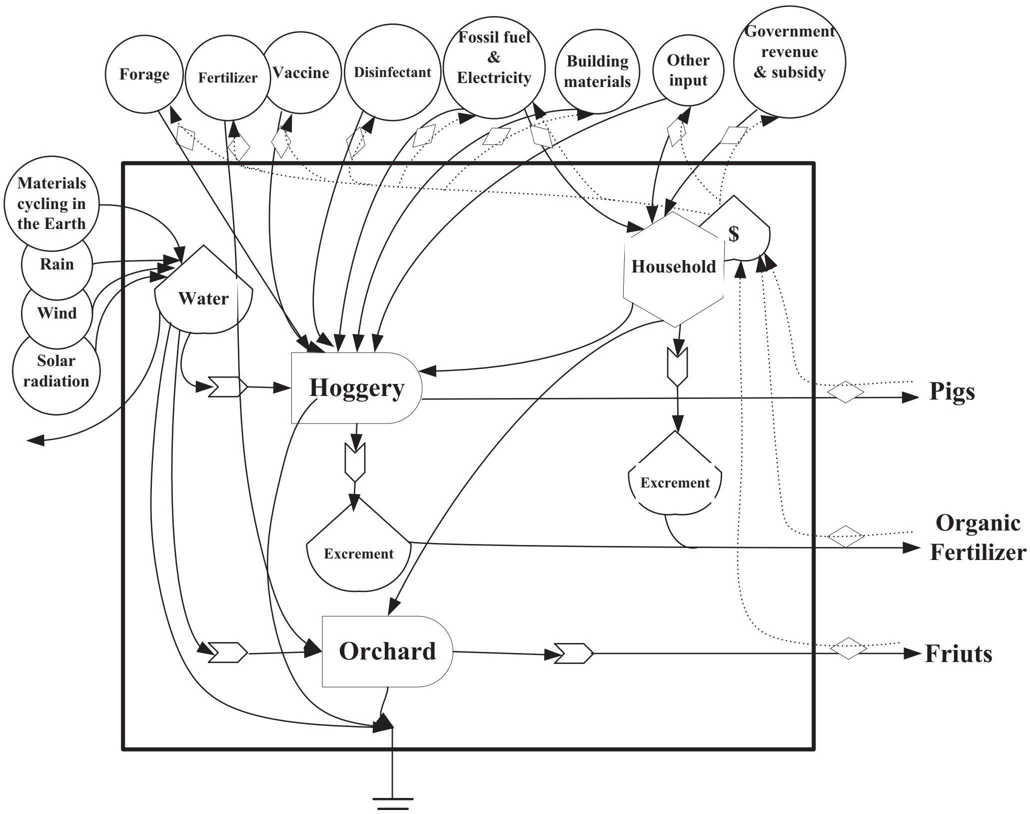

Fig. 2. The input–output-flows system before domestic biogas unit construction.

By considering the actual conditions in Gongcheng, we were able to determine the value of several factors as follows: (1) working time for a single day is an average of 10 h; (2) the prices in this table represent the average prices in China and were sourced from questionnaires and websites; and (3) the average biogas composition is 60–70% CH_4 in China, and for this study we use the value of 65% CH_4.

3. Results

We conducted a multi-objective accounting analysis for the rural biogas-linked agro-ecosystem as detailed: cost accounting and substitution benefit from the perspective of peasant households, forest protection, emission reduction based on ecological considerations, direct and indirect social amelioration, as well as the EEA analysis of four elements.

3.1. Cost accounting and substitution benefit

Based on the LCA framework and available data, an overall substitution benefit accounting for the household biogas-linked agro-ecosystem in Gongcheng was carried out in Table 2. We calculated different economic input lists as well as the output saving or earning detailed account, in which the minus sign "−" here means input saving or output earning, which directly refers to economic saving or increase in benefit.

Biogas construction started in Gongcheng in 1984 and was in wide use by 2000. At present, Gongcheng has the largest penetration of household biogas systems in the nation. The exchange rate was 8.27 Yuan per USD at the end of 2000, and during the past 10 years, the exchange rate has been in a declining trend. For this reason we presumed the exchange rate to be 8 Yuan per USD in this study to transform the economic value. In Table 2, it is shown that $247 was invested in the preliminary construction period, and in the following 10 years of optimal performance, multipurpose use such as reductions in firewood use, electricity, feed, fertilizers, and increasing fruit yields, could save $677 yearly, implying a total net substitution benefit of $6520 for each household compared with no biogas-linked peasants. From the LCA perspective, the economic input mainly existed in the first period of household biogas facility building, but after one year's operation the original input cost could be recovered by increases in production and decreases in the use of commercial fertilizers by using biogas residue and slurry. Fig. 4 demonstrates the substitution benefit structure for peasants using a one-household biogas unit, in which reductions in the use of firewood and increases in fruit production are the primary contributors to the percentage total of 79.77%. Moreover, there is also reduction in electricity, feed, and fertilizer.

3.2. Ecological benefit

Fig. 2 shows that a household biogas project can replace firewood consumption. In addition, felling and combustion emissions are dramatically reduced. An 8 m^3 household biogas unit in Gongcheng could on average save 2876 kg in firewood. In southwest China [62], the mean forest volume estimation (FVE) was 4290 cm^3/m^2. If the average outturn percentage was 72%, firewood production amounted to 3000 cm^3/m^2; therefore, the total firewood saving is 1266.67 m^2 for each household biogas unit. Furthermore, 2876 kg of firewood is equal to 1642 kg etc. (standard coal equivalent), which indicates a reduction in CO_2 and SO_2 emissions by cooking with biogas. In Table 3, we list the related emission factors for an 8 m^3 household biogas project in Gongcheng. The data were sourced from the questionnaire survey accounting results and conversion coefficients from Dai et al. [59]. The total substitution benefit of forest protection as well as emission reduction are listed in Table 4, in which 4120 kg of CO_2

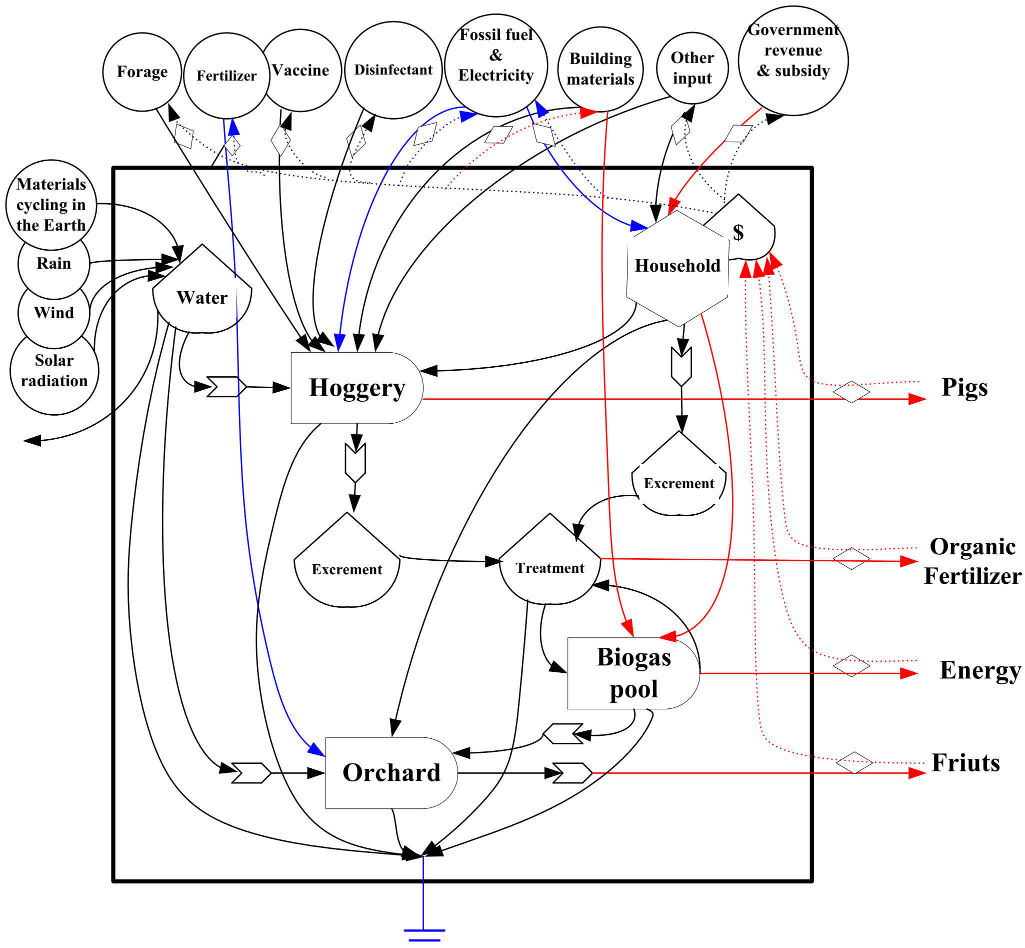

Fig. 3. The input–output-flows system after domestic biogas unit construction.

Table 1
The primary economic and exergetic data of a typical household biogas system in Gongcheng.

	Items	Number	Unit	Price (or labor)	Exergy conversion factor	Exergy conversion factor source
Construction period	Cement (425#)	1.30	t	400 RMB/t	7.41×10^7 J/t	[59,60]
	Grit	3.30	t	60 RMB/t	3.3×10^7 J/t	[59,60]
	Grait	8.10	t	80 RMB/t	3.3×10^7 J/t	[59,60]
	Plastic pipe	4.00	kg	12 RMB/kg	3.09×10^9 J/kg	[59,60]
	Steels	1.50×10^1	kg	4 RMB/kg	1.63×10^8 J/kg	[59,60]
	Brick	2.00×10^2	kg	0.3 RMB/kg	6.87×10^6 J/kg	[59,60]
	Gasoven	1.00	-	150 RMB	/	
	Skilled labor	5.00	person	20 RMB/person	1.37×10^8 J/(person × day)	[61,62]
	Ordinary labor	1.00×10^1	person	10 RMB/person	1.37×10^8 J/(person × day)	[61,62]
	Other	-	/	90 RMB	/	-
Running period	Daily management	0.5	h/day	1 person/time	1.37×10^8 J/(person × day)	[61,62]
	Yearly large refueling	1	time	12 person/time	1.37×10^8 J/(person × day)	[61,62]
Multipurpose use period	Gas production	8.67×10^2	m^3	8 RMB/kg (1.215 kg/m^3)	23.4×10^3 J/kg	[60]
	Firewood replacement	3.13	kg/m^3 gas	100 RMB/t	1.45×10^7 J/kg	[49]
	Electricity generation	4.50×10^1	kW h	0.6 RMB/kW h	1.2×10^8 J/kW h	[59,60]
	Increased fruits	1.20×10^3	kg/household	2 RMB/kg	1.9×10^6 J/kg	[49]
	Feed saving	2.00×10^2	kg/household	4 RMB/kg	5.24×10^8 J/kg	[59,60]
	Nitrogen fertilizer saving	6.99×10^1	kg (N)	2.1 RMB/kg $CO(NH_2)_2$	7.26×10^7 J/kg	[59,60]
	Phosphate fertilizer saving	2.75×10^1	kg (P_2O_5)	0.6 RMB/kg 16% (P_2O_5)	4.86×10^7 J/kg	[59,60]
	Potassic fertilizer saving	1.23×10^2	kg (K_2O)	3 RMB/kg 50% K_2SO_4	2.64×10^6 J/kg	[59,60]

and 34.7 kg of SO_2 emissions are reduced, corresponding to at least 1.86×10^9 J and 1.70×10^7 J of environmental emission exergy saved by the extra input of managing or eliminating environmental waste emissions. The forest coverage in Gongcheng in 2010 was 79.7% [50], which is significantly ascribed to the use of biogas instead of firewood.

3.3. Direct and indirect social amelioration

3.3.1. Direct carbon trading value

To better evaluate the social amelioration value of a biogas project, we considered the international CO_2 economic exchange value as an important indicator, as biogas utilization can reduce

Table 2
Biogas-linked agro-ecosystem substitution benefit per household in Gongcheng.

	Items	Number	Unit	Price (or labor)	Economic cost ($)
Construction period	Cement (425#)	1.30	t	400 RMB/t	6.50×10^1
	Grit	3.30	t	60 RMB/t	2.48×10^1
	Grait	8.10	t	80 RMB/t	8.10×10^1
	Plastic pipe	4.00	kg	12 RMB/kg	6.00
	Steels	1.50×10^1	kg	4 RMB/kg	7.50
	Brick	2.00×10^2	kg	0.3 RMB/kg	7.50
	Gasoven	1.00	/	150 RMB	1.88×10^1
	Skilled labor	5.00	Person	20 RMB/person	1.25×10^1
	Ordinary labor	1.00×10^1	Person	10 RMB/person	1.25×10^1
	Other	/	/	90 RMB	1.13×10^1
Running period	Daily management	0.5	h/day	1 person/time	/
	Yearly large refueling	1	Time	12 person/time	/
Multipurpose use period	Firewood replacement	2.71×10^3	kg	100 RMB/t	-3.39×10^1
	Electricity generation	4.50×10^1	kW h	0.6 RMB/kW h	−3.38
	Increased fruits	1.20×10^3	kg/Household	2 RMB/kg	-3.00×10^2
	Feed saving	2.00×10^2	kg/Household	4 RMB/kg	-1.00×10^2
	Nitrogen fertilizer saving	6.99×10^1	kg (N)	2.1 RMB/kg $CO(NH_2)_2$	-3.93×10^1
	Phosphate fertilizer saving	2.75×10^1	kg (P_2O_5)	0.6 RMB/kg 16% (P_2O_5	-2.95×10^1
	Potassic fertilizer saving	1.23×10^2	kg (K_2O)	3 RMB/kg 50% K_2SO_4	-1.71×10^2
Construction input	/	/	/	/	2.47×10^2
Yearly output	/	/	/	/	-6.77×10^2
Total net benefit	/	/	/	/	-6.52×10^3

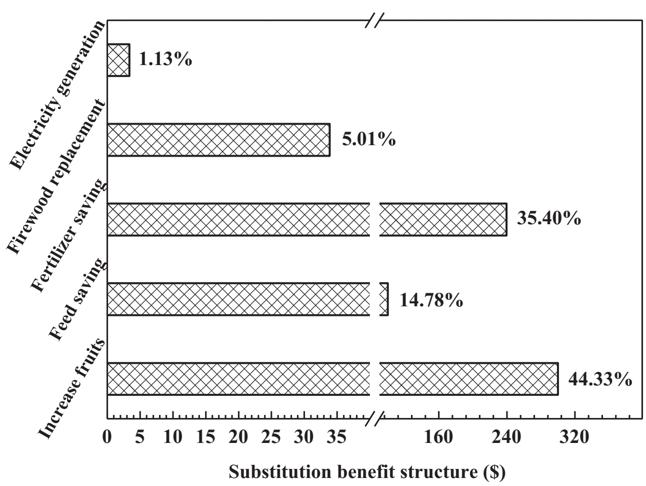

Fig. 4. Substitution benefit structure for the typical household biogas project in Gongcheng.

Table 3
The forest protection and emission reduction accounting for an 8 m^3 household biogas project in Gongcheng.

Item	Value	Unit
Gas production	8.67×10^2	m^3 Gas
Firewood replacement	3.13	kg/m^3 Gas
Forest stocking rate	4.30×10^{-3}	m^3/m^2
Pure Wood Produced rate	72%	/
Density of wood	4.67	kg/m^2 Firewood
Conversion rate of SCE/Firewood	57.09%	kg SCE/kg Firewood
CO_2 emission	2.66	kg CO_2/kg SCE
SO_2 emission	2.24×10^{-2}	kg SO_2/kg SCE
SCEx of CO_2	4.52×10^2	kJ/kg
SCEx of SO_2	4.89×10^3	SCEx kJ/kg

CO_2 emissions and the carbon emission trade is a social global marketing mechanism for emission reduction and low carbon development. On the basis that the international CO_2 exchange price was $10/t at the end of 2011 [63], the total CO_2 emission reduction cost was $41.2 per household for the whole life (construction and operation) of one biogas unit. As there were 658,000 household biogas tanks in Gongcheng in 2011 [50], the resulting reduction in CO_2 emissions would equal to $\$2.34 \times 10^7$.

Table 4
The total ecological benefit of forest protection and emission reduction for a household biogas project in Gongcheng.

	Value	Unit
Forest protection area	5.81×10^2	m^2
Reduction amount of CO_2 emission	4.12×10^3	kg
Reduction amount of SO_2 emission	3.47×10^1	kg
Reduction exergy of CO_2 emission	1.86×10^9	J
Reduction exergy of SO_2 emission	1.70×10^8	J

Table 5
The cumulative exergy consumption **(CEC)** input of one 8 m^3 household biogas unit in an LCA perspective in Gongcheng.

	Items	Exergy (J)	Effect
Construction period	Cement (425#)	9.63×10^7	+
	Grit	2.67×10^8	+
	Grait	1.09×10^8	+
	Plastic pipe	1.24×10^{10}	+
	Steels	2.45×10^9	+
	Brick	1.37×10^9	+
	Other	/	/
Multipurpose use period	Cooking	3.93×10^{10}	−
	Lighting	5.40×10^9	−
	Increased fruits	2.28×10^7	−
	Feed saving	1.05×10^{11}	−
	Nitrogen fertilizer saving	5.06×10^9	−
	Phosphate fertilizer saving	1.33×10^9	−
	Potassic fertilizer saving	3.25×10^8	−

3.3.2. *Indirect social improvements*

With the popularization of biogas projects in Gongcheng, hygiene has also been greatly improved. For example, human

and animal excreta are now collected properly and essentially fermented, which reduces the spread of germs and is definitely good for the villagers' health. In addition, this project can reduce human labor and improve labor intensity, which will improve peasants' living standards and create more opportunities for surplus labor to work elsewhere. Furthermore, the construction of biogas-linked agro-ecosystems represents a significant boost for both orchard farming and household livestock in the Gongcheng area. This provides a vital force to optimize the agricultural structure for rural fields in China. There is no doubt that a large-scale biogas-linked agro-ecosystem will definitely lead to a more intensive and comprehensive development of industrial agriculture practices. The use of biogas also looks promising as an effective measure to increase agricultural production rates and peasants' incomes.

3.4. EEA analysis

We compared the EEA results of the four elements, looking at the variations between non-household biogas facilities and post-construction domestic biogas units. In Table 5, the *CEC* input items and equivalent exergy values are listed on the basis of Table 1 in Section 2.3; moreover, the effect "+" means increased input or consumption after the management of one biogas unit for each resident, and "−" refers to reduced input, consumption saving, energy generating, or harvest yields. It is clearly shown that the exergy input only existed in the construction period in the primary stage. When the biogas unit went into normal operation time, the previous waste exergy could be extracted or reused in the multi-purpose use period in the following years. This is a very important function for evaluating biogas utility and future propagation.

Based on the consideration of extended exergy parts, we calculated the labor and capital equivalent exergy input in Table 6. As stated, both labor and capital inputs were included into the construction time, while the daily and yearly operation management could be completed by peasants without employing extra workers. The project can run during the lifetime (normally 10 years) after peasants put organic waste into the tank as labor input. Only after that, the project needs extra capital exergy input for the renovation. However, most people will abandon it after 10 years because of high renovation and reparation cost. This is why we omit the capital exergy input for the operation management. The total labor and capital equivalent exergy from a LCA perspective are 4.4×10^{10} J and 1.0×10^{9} J, respectively, for a typical 8 m^3 household biogas unit in Gongcheng.

Table 7 demonstrates the accounting parameters and results for the net variation of the influenced environmental emission exergy between non-household biogas facilities and the post-construction period of the domestic biogas unit for a typical biogas unit in Gongcheng. In the present situation for average firewood cumulative volume and corresponding conversion rate, a one-unit household biogas project could save on firewood requirements that require an area of 581 m^2 per year to support productivity. Meanwhile, it could also reduce CO_2 and SO_2 emission as well as saving extra exergy input to eliminate waste gas emissions.

The net variations of the four parts of the EEA results are presented in Table 8.

Table 6
The Labour (***ee***$_L$) and Capital (***ee***$_K$) input of one 8 m^3 household biogas unit in an LCA perspective in Gongcheng.

Item	Labor equivalency	Labor exergy equivalency (J)	Capital exergy equivalency (J)
Skilled labor	5	6.87×10^8	3.35×10^8
Ordinary labor	10	1.37×10^9	6.69×10^8
Daily management	18.5	2.54×10^9	/
Yearly large refueling	12	1.65×10^9	/
Total input		4.40×10^{10}	1.00×10^9

Table 7
The influenced environmental emission exergy variation of one 8 m^3 household biogas unit in Gongcheng.

Accounting parameters	Value	Unit
Biogas generating	8.67×10^2	m^3 biogas
Firewood replacement	3.13	kg/m^3 biogas
Average firewood cumulative volume	4.30×10^{-3}	m^3/m^2 land area
Average volume ratio from firewood	72%	-
Firewood density	4.66	kg/m^2 firewood
Standard coal (SC) firewood equivalent rate	57.09%	kg SC/kg firewood
CO_2 emission	2.66	kg CO_2/kg SC
SO_2 emission	2.24×10^{-2}	kg SO_2/kg SC
CO_2 Standard chemical exergy	4.52×10^{-2}	SCEx kJ/kg
SO_2 Standard chemical exergy	4.89×10^3	SCEx kJ/kg
Accounting results		
Forest protection area	5.81×10^2	m^2
Reduced CO_2 emission amount	4.12×10^3	kg
Reduced SO_2 emission amount	3.47×10^1	kg
Reduced CO_2 emission exergy	1.86×10^9	J
Reduced SO_2 emission exergy	1.70×10^8	J

Table 8
Total net variation of four parts of EEA results for one 8 m^3 household biogas unit in Gongcheng.

EE elements	Exergy (J)
CEC	-1.57×10^{12}
ee_K	1.00×10^9
ee_L	4.40×10^{10}
ee_{Env}	-2.03×10^{10}

4. Conclusions and discussions

Many countries especially the developing ones have dramatically expanded their power sectors during the last several decades. Rural renewable energy systems have already been successfully certified in various countries as a complete small-scale household energy generator pattern offering the best option to supply electricity and daily energy consumption, especially to remote and undeveloped areas [64–66]. Meanwhile, biogas as an important renewable energy source has been increasingly taken seriously as a national coping strategy for adapting energy crisis in many countries for widely use and expansively application [67–71].

In this case study, the integrated performance of a typical household biogas project is evaluated in an LCA perspective to quantify the real economic and ecological benefits. The results show that:

(1) The household biogas construction in Gongcheng Yao Autonomous County is a positive economic stimulus program to increase peasants' income, with only $247 being invested for the first-year-construction but $677 yearly saving for multi-purpose increment. The total net substitution benefit is estimated to be $6520 for the best 10-year operation period. This is therefore a possible solution for the rural and needy families in China to increase income and reach prosperity with an input–output ratio more than 26 times in general.

(2) In the life cycle perspective, the exergy embodied in the raw materials has been extracted via tank fermentation and utilized for various end uses of household energy consumption, cropping and livestock feeding. The extended supply chain of biomass energy based on biogas-liked agro-ecosystems can successfully reduce the reliance on traditional fossil fuels and mitigate the environmental impacts, decreasing 4120 kg of CO_2 and 34.7 kg of SO_2 emissions during the 10-year operation period and avoiding more than 1.86×10^9 J extra work to eliminate the environment disturbances. Also, the potential carbon trading values of CO_2 emission reduction are respectively estimated to be \$41.2 for one biogas project and $\$2.34 \times 10^7$ for the total Gongcheng County, which are substantial tradable emission credits for local government to gain the initiative in participating the national and international carbon trading.

(3) The stage with the greatest energy or resource exergy saving is the normal operation time for ***CEC*** net input saving or output gaining, in which 1.57×10^{12} J of exergy is collected for reuse or regenerating value in the whole life of household biogas construction, running, and multipurpose use periods. Moreover, 2.03×10^{12} J of emission eliminating exergy is also saved by biogas combustion. In essence, it is the humus decomposition of excrement from animals and households that replaces the need for extra firewood consumption and waste gas emissions. However, to accomplish this sustainable exergy saving behavior, human efforts in terms of labor and capital input are necessary, with an average value of 1.0×10^9 J and 4.4×10^{10} J, respectively, in the case of Gongcheng. Therefore, the household biogas application in Gongcheng is a good example of how energy saving and emission reduction can be accomplished by artificial design and management, with a saving of 35.34 times the equivalent of physical-based exergy compared with human labor and capital equivalent exergy inputs. In addition, the surplus labor in China's rural areas is sufficient for biogas operations, and a government financial subsidy would significantly promote this positive initiative, both to alleviate the energy shortage and to improve environmental quality.

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References

[1] CSY. China statistical yearbook. Beijing: China Statistics Press; 2011.
[2] Tonooka Y, Liu JP, Kondou Y, Ning YD, Fukasawa O. A survey on energy consumption in rural households in the fringes of Xi'an city. Energy Build 2006;38(11):1335–42.
[3] Zhang LX, Yang ZF, Chen B, Chen GQ. Rural energy in China: pattern and policy. Renewable Energy 2009;34(12):2813–23.
[4] Zheng YH, Li ZF, Feng SF, Lucas M, Wu GL, Li Y, Li CH, Jiang GM. Biomass energy utilization in rural areas may contribute to alleviating energy crisis and global warming: a case study in a typical agro-village of Shandong, China. Renewable Sustainable Energy Rev 2010;14(9):3132–9.
[5] Li JF, Hu RQ. Sustainable biomass production for energy in China. Biomass Bioenergy 2003;25(5):483–99.
[6] CESY. China energy statistical yearbook. Beijing: China Statistics Press; 2007.
[7] CESY. China energy statistical yearbook. Beijing: China Statistics Press; 2010.
[8] NBSC. National Bureau of statistics of China. Beijing: China Statistics Press; 2010.
[9] Catania P. China's rural energy system and management. Appl Energy 1999;64(1-4):229–40.
[10] Wang XH, Feng ZM. Study on affecting factors and standard of rural household energy consumption in China. Renewable Sustainable Energy Rev 2005;9(1):101–10.
[11] Jiang XY, Sommer SG, Christensen KV. A review of the biogas industry in China. Energy Policy 2011;39(10):6073–81.
[12] Zhang PD, Jia GM, Wang G. Contribution to emission reduction of CO_2 and SO_2 by household biogas construction in rural China. Renewable Sustainable Energy Rev 2007;11(8):1903–12.
[13] Li JF, Hu RQ, Song YQ, Shi JL, Bhattacharya SC, Abdul Salam P. Assessment of sustainable energy potential of non-plantation biomass resources in China. Biomass Bioenergy 2005;29(3):167–77.
[14] Hall DO, Scrase JI. Will biomass energy be the environmentally friendly fuel of the future? Biomass Bioenergy 1998;15(4-5):357–67.
[15] Kartha S, Larson ED. A bioenergy primer: modernized biomass energy for sustainable development. New York, USA: United Nations Development Program; 2000.
[16] UNDP/WEC. World energy assessment: energy and the challenges of sustainability. United Nations Development Programme. United Nations Department of Economic and Social Affairs. New York, USA: World Energy Council; 2001.
[17] Berndes G, Hoogwijk M, Van den Broek R. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 2003;25(1):1–28.
[18] Zhou XP, Wang F, Hu HW, Yang L, Guo PH, Xiao B. Assessment of sustainable biomass resource for energy use in China. Biomass Bioenergy 2011;35(1):1–11.
[19] Ma HY, Oxley L, Gibson J, Li W. A survey of China's renewable energy economy. Renewable Sustainable Energy Rev 2010;14(1):438–45.
[20] Demirbas MF, Balat M, Balat H. Potential contribution of biomass to the sustainable energy development. Energy Convers Manage 2009;50(7):1746–60.
[21] Hall DO. Biomass energy in industrialised countries—a view of the future. Forest Ecol Manage 1997;91(1):17–45.
[22] Zhang PD, Yang YL, Tian YS, Yang XT, Zhang YK, Zheng YH, Wang LS. Bioenergy industries development in China: dilemma and solution. Renewable Sustainable Energy Rev 2009;13(9):2571–9.
[23] Central People's Government of the People's Republic of China; 2005. Renewable Energy Law of PR China. 〈http://www.gov.cn/ziliao/flfg/2005-06/21/content_8275.htmS〉 (in Chinese).
[24] National Development and Reform Committee of China; 2006a. Regulations related to renewable energy power generation (in Chinese).
[25] National Development and Reform Committee of China; 2006b. Renewable energy prices and cost-sharing management trial procedures (in Chinese).
[26] National People's Congress of the People's Republic of China; 2009. Renewable Energy Law (revision) of PR China. 〈http://www.npc.gov.cn/huiyi/cwh/1112/2009-12/26/content_1533216.htmS〉 (in Chinese).
[27] Chen Y, Yang GH, Sweeney S, Feng YZ. Household biogas use in rural China: a study of opportunities and constraints. Renewable Sustainable Energy Rev 2010;14(1):545–9.
[28] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renewable Sustainable Energy Rev 2011;15(5):2262–89.
[29] Qi XS, Zhang SP, Wang YZ, Wang RQ. Advantages of the integrated pig-biogas-vegetable greenhouse system in north China. Ecol Eng 2005;24(3):175–83.
[30] Chen RJ. Livestock – biogas – fruit systems in South China. Ecol Eng 1997;8(1):19–29.
[31] Byrne J, Shen B, Wallace W. The economics of sustainable energy for rural development: a study of renewable energy in rural China. Energy Policy 1998;26(1):45–54.
[32] Jiang MM, Chen B, Zhou JB, Tao FR, Li Z, Yang ZF, Chen GQ. Emergy account for biomass resource exploitation by agriculture in China. Energy Policy 2007;35(9):4704–19.
[33] Zhang PD, Yang YL, Shi J, Zheng YH, Wang LS, Li XR. Opportunities and challenges for renewable energy policy in China. Renewable Sustainable Energy Rev 2009;13(2):439–49.
[34] Yang Q, Chen B, Ji X, He YF, Chen GQ. Exergetic evaluation of corn-ethanol production in China. Commun Nonlinear Sci Numer Simul 2009;14(5):2450–61.
[35] Zhou SY, Zhang B, Cai ZF. Emergy analysis of a farm biogas project in China: a biophysical perspective of agricultural ecological engineering. Commun Nonlinear Sci Numer Simul 2010;15(5):1408–18.
[36] Byrne J, Zhou AM, Shen B, Hughes K. Evaluating the potential of small-scale renewable energy options to meet rural livelihoods needs: A GIS- and lifecycle cost-based assessment of Western China's options. Energy Policy 2007;35(8):4391–401.
[37] Mu H, Kondou Y, Tonooka Y, Sato Y, Zhou W, Ning Y, Sakamoto K. Grey relative analysis and future prediction on rural household biofuels consumption in China. Fuel Process Technol 2004;85(8-10):1231–48.
[38] Chen GQ. Scarcity of exergy and ecological evaluation based on embodied exergy. Commun Nonlinear Sci Numer Simul 2006;11(4):531–52.
[39] Sciubba E. Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems Exergy Int J 2001;1(2):68–84.
[40] Sciubba E. Exergoeconomics. In: Cleveland CJ, editor. Encyclopedia of energy. New York, USA: Elsevier Science Publishers; 2004. p. 577–91.
[41] Tainter JA. Social complexity and sustainability. Ecol Complexity 2006;3(2):91–103.
[42] Ertesvåg IS. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 2005;30(5):649–75.

[43] Milia D, Sciubba E. Exergy-based lumped simulation of complex systems: an interactive analysis tool. Energy 2006;31(1):100–11.
[44] Sciubba E, Bastianoni S, Tiezzi E. Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy. J Environ Manage 2008;86(2):372–82.
[45] Gasparatos A, El-Haram M, Horner M. Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. Renewable Sustainable Energy Rev 2009;13(5):1074–81.
[46] Gasparatos A, El-Haram M, Horner M. Assessing the sustainability of the UK society using thermodynamic concepts: Part 2. Renewable Sustainable Energy Rev 2009;13(5):956–70.
[47] Ptasinski KJ, Koymans MN. Verspagen HHG. Performance of the Dutch Energy Sector based on energy, exergy and Extended Exergy Accounting. Energy 2006;31(15):3135–44.
[48] Seckin C, Sciubba E, Bayulken AR. An application of the extended exergy accounting method to the Turkish society, year 2006. Energy 2012;40 (1):151–63.
[49] Chen GQ, Chen B. Extended-exergy analysis of the Chinese society. Energy 2009;34(9):1127–44.
[50] GWRG, Government Work Report in Gongcheng; 2011. ⟨http://www.gx.xinhuanet.com/dtzx/2011-02/24/content_22137046.htm⟩ (in Chinese).
[51] Corrado A, Fiorini P, Sciubba E. Environmental assessment and extended exergy analysis of a zero CO_2 emission, high-efficiency steam power plant. Energy 2006;31(15):3186–98.
[52] ISO 14040 International Standard Environmental Management – Life Cycle Assessment – Principles and Framework International Organisation for Standardization, Geneva, Switzerland; 2006.
[53] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S. Recent developments in life cycle assessment. J Environ Manage 2009;91(1):1–21.
[54] GCEIN, Gongcheng Economic Information Network 2010. ⟨http://gc.glin.cn/⟩ (in Chinese).
[55] GCAIN, Gongcheng Agriculture Information Network; 2010. ⟨http://www.glgcagri.gov.cn/⟩ (in Chinese).
[56] CEIN, China Economic Information Network; 2010. ⟨http://www.cei.gov.cn/⟩ (in Chinese).
[57] GLEIN, Guilin Economic Information Network; 2010. ⟨http://www.gx.cei.gov.cn/⟩ (in Chinese).
[58] GCCGN, Gongcheng County Government Network; 2010. ⟨http://www.gx.xinhuanet.com/dtzx/guilin/gongcheng/⟩ (in Chinese).
[59] Dai J, Chen B, Sciubba E. Ecological accounting based on extended exergy-a sustainability perspective. Environ Sci Technol 2014;48:9826–33. http://dx.doi.org/10.1021/es404191v.
[60] Dai J, Fath B, Chen B. Constructing a network of the social-economic consumption system. Renewable Sustainable Energy Rev 2012;16(7): 4796–808.
[61] Chen B, Chen SQ. Life cycle assessment of coupling household biogas production to agricultural industry: a case study of biogas-linked persimmon cultivation and processing system. Energy Policy 2013;62:707–16.
[62] Chen SQ, Chen B, Song D. Life-cycle energy production and emissions mitigation by comprehensive biogas-digestate utilization. Bioresour Technol 2012;114:357–64.
[63] CTN, Carbon Trading Network; 2011. ⟨http://www.sxcoal.com/cbontw/index.html⟩, ⟨http://finance.jrj.com.cn/2011/11/30103211683743.shtml⟩ (in Chinese).
[64] Cherni JA, Hill Y. Energy and policy providing for sustainable rural livelihoods in remote locations—the case of Cuba. Geoforum 2009;40(4):645–54.
[65] Cynthia Neudoerffer R, Malhotra P, Venkata Ramana P. Participatory rural energy planning in India - a policy context. Energy Policy 2001;29(5):371–81.
[66] Wolde-Ghiorgis W. Renewable energy for rural development in Ethiopia: the case for new energy policies and institutional reform. Energy Policy 2002;30 (11-12):1095–105.
[67] Maghanaki MM, Ghobadian B, Najafi J, Galogah RJ. Potential of biogas production in Iran. Renewable Sustainable Energy Rev 2013;28:702–14.
[68] Hosseini SE, Wahid MA. Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia. Renewable Sustainable Energy Rev 2013;19:454–62.
[69] Poeschl M, Ward S, Owende P. Prospects for expanded utilization of biogas in Germany. Renewable Sustainable Energy Rev 2010;14:1782–97.
[70] Kim YS, Yoon YM, Kim CH, Giersdorf J. Status of biogas technologies and policies in South Korea. Renewable Sustainable Energy Rev 2012;16:3430–8.
[71] Budzianowski WM. Sustainable biogas energy in Poland: prospects and challenges. Renewable Sustainable Energy Rev 2012;16:342–9.

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